DRCS: A Distributed Routing and Channel Selection Scheme for Multi-Channel Wireless Sensor Networks

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***Abstract*—We propose a joint channel selection and quality aware routing scheme for multi-channel wireless sensor networks to improve the network lifetime. A data collection traffic pattern is assumed, where all sensor nodes perform periodic sensing and forward data to a centralized base station (sink). The proposed scheme achieves improvement of the battery lifetime by reducing the energy consumed from overhearing and also by dynamically balancing the battery lifetimes of nodes. Performance evaluations are presented from experimental studies as well as from extensive simulation studies to show the effectiveness of the proposed scheme.**

***Keywords*-Wireless sensor networks; multi-channel routing; distributed algorithms.**

I. Introduction

Development of new approaches for optimizing energy usage is a key issue for achieving reliable and long-term operation of wireless sensor networks (WSNs). Since batteries are hard to replenish, energy optimization is a critical design requirement for all protocols and algorithms for WSNs. The popular approach for energy optimization in WSNs involves development of methods for minimizing the number of radio transmissions and/or receptions, which is the dominating factor in the energy consumption in sensor nodes. The complexity of this energy optimization problem in sensor networks arises due to the fact that it has to be addressed by *network wide* adaptations as opposed to independent adaptations at the nodes.

We consider large-scale WSNs for data collection applications, where implementation of network-wide time synchronization is a significant challenge. Hence, it is difficult to apply synchronized duty cycling and scheduled transmissions in such networks, which are critical for avoiding energy wastage from *overhearing*. In this work, we propose the use of multiple orthogonal channels to alleviate the overhearing problem and thereby improve the network lifetime. Current WSN platforms such as MICAz and Telos that use CC2420 radio can operate on multiple channels, which are traditionally used to address interference problems. We develop a quality and battery-health aware *Distributed Routing and Channel Selection (DRCS)* scheme that dynamically chooses channels and routes to optimize network lifetime and performance. The objective is to dynamically control the power consumption of the nodes so as to *equalize their remaining lifetimes* as estimated from their current battery capacity and usage. The performance of DRCS is obtained from experiments using a MICAz testbed as well as from simulations. Performance comparison with an existing multi-channel routing protocol for WSNs is also presented from simulations. This work is an extension of our previous work that was presented in [1], where we discussed a distributed channel selection scheme based on hop-counts and battery healths of the nodes.

II. Related work

Multi-channel routing in wireless networks has received a lot of attention in recent times [2], [3], [4], [5]. However, most of the work published in this area either assume a multi-radio transceiver at each node or generate high control overhead for channel negotiation. Much of this work focuses on reducing the complexity of solving the joint channel selection and routing problem. These schemes are not suitable for WSNs where each sensor is typically equipped with single radio transceiver and has limited computational capabilities. In addition, overhead must be minimized since energy resources are at a premium. Some multi-channel MAC protocols for WSNs such as MMSN [6], TMMAC [7], MMAC [8] are designed for single radio interfaces per node. However, they require precise time synchronization, which is hard to obtain in large scale WSNs.

Recently, some strategies for joint channel assignment and routing for WSNs were proposed in [9], [10], [11]. In [9], the authors propose a tree-based multichannel protocol (TMCP) where the whole network is statically divided into mutually exclusive single-channel subtrees to reduce interference. Authors in [10] propose a control theory approach that selects channel dynamically to achieve load balancing among channels, whereas in [11] authors propose a channel assignment scheme for WSNs based on game theory to reduce interference. All of the above schemes mainly consider reducing network interference, which is not a major concern in sensor networks with low density activities. Also, some of the above approaches are either centralized or

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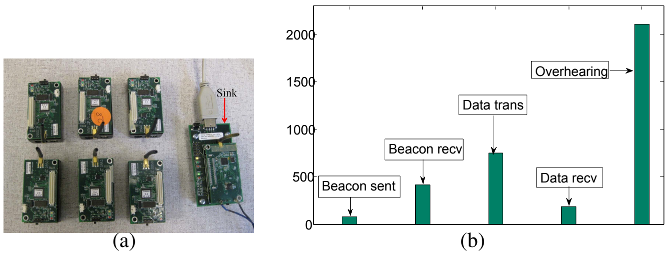

Figure 1. Experimental setup (a) to assess the activities of the radio (b) of a wireless sensor node performing data collection.

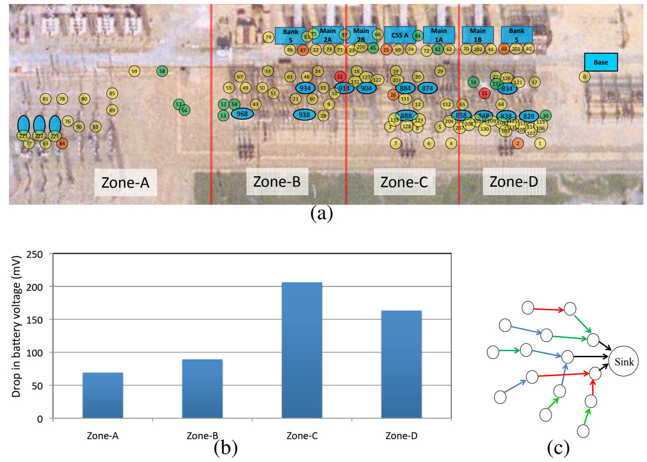

Figure 2. Illustration of the layout (a) of *ParadiseNet* [12], a 122-node WSN deployed for equipment health monitoring from a power substation, and the average battery usage of nodes in different geographical zones over a period of five months (b). *ParadiseNet* uses a single-channel link quality based routing protocol. The goal of this work is to develop a multi-channel tree for such WSNs to extend its lifetime (c).

need the topology information that is not always possible to obtain in WSNs. As opposed to these contributions, the proposed DRCS protocol performs channel selection and routing together for improving the battery lifetime in WSNs. Furthermore, DRCS is distributed, can be applied without time synchronization, and requires a single transceiver per node.

III. Motivation Behind This Work

Radio transmissions as well as receptions are the critical energy-consuming tasks in typical low-powered wireless sensor nodes. For instance, the MICAz nodes draw about $20mA$ of current while transmitting and receiving, whereas it draws about 20 μA in idle mode and $1\mu A$ in sleep mode. Hence, a key approach for achieving energy efficiency is to minimize the radio active periods, allowing the node to sleep as long as possible. Popular energy efficient wireless sensor networking protocols such as $XMesh$ [12] employs low-power (LP) operation by letting nodes duty cycle in their sleep modes for brief periods of time to detect possible radio activity and wake up when needed. While this principle extends the battery life (lifetime) of the nodes considerably, a significant factor that affects the energy consumption is *overhearing*, i.e. receiving packets that are intended for other nodes in the neighborhood. The traditional mechanism used for avoiding overhearing is transmission scheduling, which requires time synchronization that we assume is absent in the WSNs.

The effect of overhearing is illustrated in Figure 1, which depicts an experiment using six MICAz motes and a sink. The network is programmed with the *collection tree protocol (CTP)* [13] application where each node transmits periodic data packets comprising of sensor observations with an interval of 10 seconds and routing packets (beacons) with an interval that varies between 128 and 512000 milliseconds. The network uses the beacons to build link quality based least-cost routes from all nodes to the sink. All nodes are programmed with an extremely low transmit power of -28.5 dBm and the *LowPowerListening* scheme [14] with a wake-up interval of 125 milliseconds. We run this experiment for 10 minutes and record the total number of beacon and data packets sent/received throughout the network as well as the network wide overhearing. The results, shown in Figure 1(b), indicate that the number of overhearing events is significantly higher than all other events in the radio, and hence it is a dominating factor in the energy consumption of the nodes. Consequently, our primary objective is to develop a mechanism to optimally distribute the network traffic over multiple channels, which will lead to reduction in overhearing and improvement in the lifetime of the network.

In addition to reducing overhearing, a second consideration for improving the network lifetime is to address the effect of *differential battery drainage* among the nodes. This is motivated by experimental observations from a WSN testbed that was developed by the authors for health monitoring of high-power equipment in a power substation in Figure 2. The WSN, called *PradiseNet* [15], consists of 122 wireless sensor nodes that were deployed in 1000×400 feet area, and uses a link-quality based routing protocol. Figure 2(a) depicts the locations of nodes in *ParadiseNet* and Figure 2(b) depicts the average drops in the battery levels in the four regions of the network over a period of five months of operation. It can be observed that while nodes closer to the base station generally have higher voltage drops, Zone-C has the highest drop. The primary reason for this is that sensor nodes in Zone C are responsible for forwarding most of the packets from Zone A and Zone B. In addition, nodes from Zone C also experience higher amount of overhearing traffic. This type of energy imbalance ultimately results in nodes in Zone C depleting their batteries earlier than the ones in other zones which will collectively result in network partitioning and decrease in the lifetime of the network. Consequently, it is important that in addition to addressing the overhearing problem, the energy consumption in the nodes should be balanced so that the network lifetime is maximized.

IV. Multi-Channel Routing in WSNs

In *data collecting* wireless sensor networks, the forwarding scheme follows a tree structure connecting the nodes to the sink. With a single channel, a node overhears all nodes that are in the receiving range of that node. Our first objective is to use a multi-channel tree so that the overhearing problem is reduced. In our scheme, the available channels are distributed among the nodes so that each node listens on its selected channel by default. For data transmissions and forwarding, each node temporarily switches to the channel of its parent and switches back to its designated channel when the transmission is completed. Selection of designated channels as well as parents are performed based on a battery health parameter H and a path metric that is calculated using a link quality parameter (ETX), as explained below. While channel selection builds a multi-channel tree that is the primary mechanism for overhearing reduction (see illustration in Figure 2(c), where different channels are shown in different colors), it also builds the framework for dynamic route and channel selection to achieve load balancing, which is designed to meet our second objective of lifetime equalization.

A. Preliminaries

We define the battery *health-metric* H of a node to represent its remaining battery lifetime, i.e. the estimated time until its battery is depleted under its currently estimated energy usage. We assume $H \propto \frac{B}{\mathcal{I}}$, where B is the remaining capacity of the battery and $\mathcal{I}$ represents the estimated current drawn at the node. Based on the experimentally validated model [15], the current drawn in each node is calculated as follows:

$$\begin{aligned} \mathcal{I} &= \frac{I_{Bt}T_{Bt}}{T_B} + M.I_{Dt}T_{Dt} + N.\frac{I_{Br}T_{Br}}{T_B} + O.I_{Dr}T_{Dr} \\ &+ F.I_{Dt}T_{Dt} + \frac{I_sT_s}{T_D} + N_P.I_PT_P \qquad (1) \end{aligned}$$

where I_x and T_x represent the current drawn and the duration, respectively, of the event x; and T_B represents the beacon interval. Transmission/reception of beacons is denoted by B_t/B_r, data transmit/receive is denoted by D_t/D_r and processing and sensing are denoted as P and S, respectively. O and F are the overhearing and forwarding rates, respectively, and N is the number of neighbors. M is the rate at which a node transmits its own packets. If there are no retransmissions, then $M = \frac{1}{T_D}$, where T_D is the data interval. N_P represents the number of times that a node wakes per second to check whether the channel is busy, and is set to 8 in our application. We assume that each node is able to estimate all the dynamic parameters that are used in equation (1), by periodic assessment of its overheard and forwarded traffic.

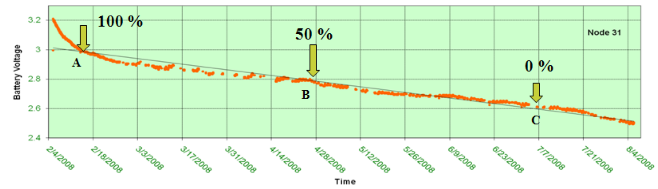

Figure 3. Battery discharge curve of a typical node in *Paradisenet*

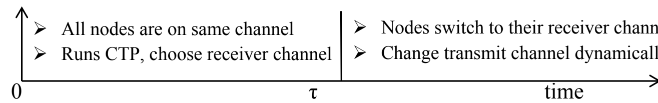

Figure 4. The proposed channel selection scheme in DRCS

In this work, we assume that the battery capacity B is estimated from the battery voltage. We consider MICAz nodes, which operate in a voltage range of 2.7V to 3.3V [16]. Experimental data from *ParadiseNet* indicates that the discharge curve for alkaline cells under typical usage (i.e. $< 1mA$ average current) is approximately linear within this range. This is illustrated in Figure 3. The actual battery voltage is related to the ADC reading as follows: $V_{bat} = \frac{1.223 \times 1024}{\text{ADC reading}}$. Thus, assuming that the capacity is 100% when the battery voltage is greater than or equal to 3V (ADC reading = 417 from MICAz voltage sensor), and 0% when it drops below 2.6V (ADC reading = 482), the battery capacity can be estimated as $B = \min\left(100, \frac{482 - \text{ADC reading}}{0.65}\right)$. Although this is not an accurate estimate, it provides a computationally simple assessment of the battery health[1].

To estimate the quality of a route, we use a path metric that is obtained as the sum of the *expected number of transmissions (ETX)* on each of its links, which is the same principle applied in CTP. An ETX for a link is the expected number of transmission attempts required to deliver a packet successfully over the link. In CTP, path selection is performed as follows. The sink always broadcasts a path metric = 0. A node i chooses node j as its parent among all its neighbors if ETX_{ij} + path vector of $j <$ ETX_{ik} + path vector of k $\forall k \neq j$. In this process a node chooses the route with the lowest path metric to the sink.

B. The Proposed DRCS Scheme

We now present the proposed distributed channel selection and routing scheme DRCS for single-radio WSNs that distributes transmission over multiple channels and tries to balance the remaining lifetimes of all nodes in the network. We define the *receiver channel* of a node to be its designated channel for receiving all incoming packets. On the other

[1] A more accurate method for estimating the battery capacity is currently being implemented, which is beyond the scope of this work.

hand, a *transmit channel* is the channel to which a node temporarily switches to transmit a packet, which is the receiver channel of its intended destination. According to DRCS, nodes select their receiver channels to enable distribution of traffic over multiple orthogonal channels. Nodes listen on their receiver channels by default, and hence overhearing is limited to neighboring transmissions on a node's receiver channel only. Transmit channels are chosen dynamically to prolong the lifetime of the *neighboring node with the worst battery health-metric*. Note that channel selection is tied to parent selection, which leads to route determination. Hence the proposed approach leads to a joint channel selection and routing in the WSNs.

As shown in Figure 4, the channel selection scheme in DRCS runs in two stages, which are described below. We assume that all nodes broadcast periodic beacon messages, which include their node ID, receiver channel, path metric and battery health-metric. This is performed at intervals called route-update interval (RUI), each time over a different channel that is chosen in a round-robin fashion.

First stage: In this stage, all nodes use a common default channel. Each node chooses a random backoff (this ensures that nodes choose channels one after another) and selects *the least used channel in its neighborhood* when the backoff timer expires. This channel becomes the node's receiver channel, which it announces to its neighbors via beacon packets. If there are multiple channels that are least used, the tie is broken by choosing a random channel among the channels that make the tie. All nodes store their neighbors as well as the neighbors' receiver channel information. After a certain time interval τ, the second stage begins. At the end of the first stage, all nodes select their receiver channels so as to minimize overlap in their neighborhoods, in a distributed fashion. Nodes also determine their path metrics to the sink by running CTP over the default channel.

Second stage: In the second stage, all nodes switch to their receiver channels. In this stage, nodes dynamically perform parent selection, and consequently, their transmit channels, based on periodic assessments of the battery health and path metric parameters. This is done as follows. For any channel c, each node calculates $\mathcal{H}_c$ = min$\{H_i\}$ $\forall$ $i \in S_c$ where S_c is the set of neighbors that are in receiver channel c and H_i is the health metric of node i. In order to transmit to the sink, the common default channel is chosen, which is the receiver channel of the sink. For all other transmissions (i.e. for transmitting to nodes other than the sink) the transmitting node chooses a transmit channel c with a probability of $\frac{\mathcal{H}_c}{\mathcal{H}} \cdot \frac{1}{e_c}$, where $\mathcal{H} = \sum \mathcal{H}_i$ $\forall$ channel i in the node's neighborhood such that there is at least one neighbor that is in channel i and whose path metric is less than the node's path metric. e_c is the ETX of the link between a node and the neighbor in c that has the lowest path metric to the sink. The term $\frac{\mathcal{H}_c}{\mathcal{H}}$ ensures that the receiver channel of the node with the worst health-metric is chosen with the lowest probability. This mechanism *minimizes the overhearing for the neighboring nodes with low health-metrices*. The term $\frac{1}{e_c}$ represents the probability that the packets sent by a node are received successfully by its parent if channel c is chosen. After choosing the transmit channel, a node chooses the parent among all its neighbors on c that has the best path metric to the sink. Nodes choose transmit channels as well as their parents at intervals of RUI.

The routing and channel selection scheme should ensure that new nodes that are added to the network at any time are able to get connected to the network and send informations to the sink. In our proposed scheme, this is ensured by sending the beacon messages in different channels in rotation. Hence, a new node is always able to receive beacons from its neighbors and get connected, irrespective of its choice of the receiver channel.

C. Characteristics of DRCS

The proposed routing and channel selection scheme takes into account a number of factors that are explained as follows:

Battery state of individual nodes: The battery state of a node is taken into account by the term B. If the battery condition of any node deteriorates, the value of its health-metric will drop. This will result in a lower probability of selection of that node's channel by its neighboring nodes for DATA transmission.

Load balancing between nodes: If a node's load increases, its $\mathcal{I}$ will increase, causing its health-metric to decrease. This will cause that node's channel to be chosen with lower probability in the next RUI. Also after choosing the transmit channel, a parent is chosen based on the lowest path metric. Thus, if a parent is overloaded, the value of its path metric will increase, resulting in other nodes to avoid selecting that node.

Load balancing between channels: If a channel is overused, the forwarding and overhearing traffic on that channel will increase. This will decrease the health-metric of the nodes in that channel. Thus, that channel is avoided in the next RUIs with higher probability.

Route quality: The value of the path metric quantifies the quality of a route. The route quality is important as bad routes result in higher retransmissions, which reduce the network lifetime.

Channel quality: DRCS favors selection of channels with better quality, i.e. lower interference, as follows. A high level of channel interference will result in higher number of retransmissions and overhearing on that channel, causing the health-metrices of the nodes on that channel to reduce. Moreover, it will increase the e_c for that channel. Consequently, the corresponding channel will be chosen with lower probability in the next RUIs.

The proposed scheme does not incur any additional control overhead other than periodic beacon updates. Also, to

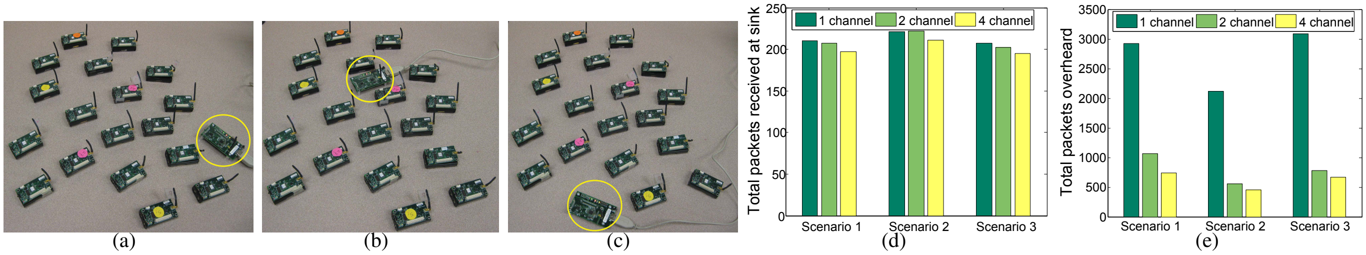

Figure 5. Experimental deployment scenarios with sink locations marked by yellow circles: 1 (a), 2 (b), and 3 (c); and comparison of the number of packets delivered at the sink (d) and the total packets overheard (e), with 1, 2, and 4 channels.

avoid *idle listening*, nodes use low-power listening where they sleep most of the time and wake up in periodic intervals. If they sense some channel activity, they remain on. Otherwise, they go back to sleep to conserve energy. Problems such as routing loop detection and repairing are tackled similar to CTP. One possible drawback of DRCS is the possibility of frequent channel switching which happens when the receive and transmit channels of a node are different. Channel switching introduces time delays as well as additional power consumption in the nodes, which has been ignored in this work. Our experimental results demonstrate that in data collection applications with low data rates, the channel switching delay does not affect the delivery ratio significantly. However, for high data rate applications, frequent channel switching may result in some data loss as well as additional energy consumption.

V. Performance Evaluation

This section presents evaluation results of DRCS that are obtained from and experimental testbed as well as from simulations. We first demonstrate that our proposed multi-channel scheme effectively reduces overhearing using an experimental testbed comprising of 18 MICAz motes. The experimental tests also demonstrate the effectiveness of the dynamic channel selection scheme based on individual node's battery health metrices. To show the performance of our scheme in a larger network, we implement this scheme in the *Castalia* simulator [17] on a 150-node network. Finally, we compare the performance of DRCS with a well-known tree-based multi-channel scheme TMCP. Parameters used for experiments and simulations are listed in Table I.

Table I
Simulation environment

Var	Values	Var	Values	Var	Values	Var	Values
I_{Bt}	20 mA	T_{Bt}	140 ms	I_{Br}	20 mA	T_{Br}	140 ms
I_{Dt}	20 mA	T_{Dt}	140 ms	I_{Dr}	20 mA	T_{Dr}	140 ms
I_P	8 mA	T_P	3 ms	I_S	7.5 mA	T_S	112 ms

A. Evaluation in an experimental testbed

We implement our proposed scheme DRCS in TinyOS using MICAz motes that use LowPowerListening with wake-up intervals of 125 milliseconds. The beacon interval, DATA

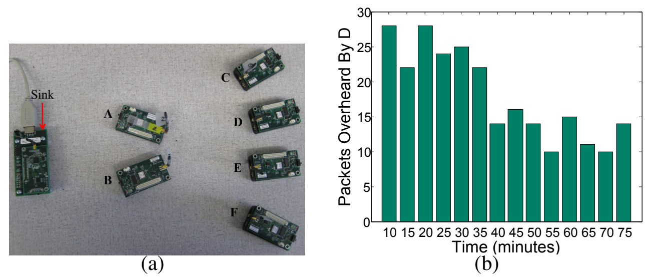

Figure 6. Experiment to evaluate the effectiveness of dynamic transmit channel selection.

interval and τ are chosen to be 30, 60 and 180 seconds respectively. The transmit power is chosen to be -28.5 dBm to enable experimentation in a small place. We place 18 motes that periodically sense and forward sensor data to the sink using our proposed multi-channel routing scheme DRCS. We perform experiments using three difference scenarios, all having the same network topology but with different sink locations. These are shown in Figure 5(a)-(c). For ease of obtaining packet counts, we disable retransmissions in these experiments. The results obtained over a duration of 15 minutes are shown in Figure 5(d)-(e). It is observed that in all three scenarios, the number of packets received at the sink drops only marginally with increasing number of channels, even with no retransmissions. This implies that the packet delivery performance is not significantly affected by the channel switching delay in these data-rates. However, there is a significant reduction in the total number of overhearing packets by using 2 and 4 channels. This experiment demonstrates that DRCS can significantly reduce energy wastage due to overhearing without sacrificing the delivery performance.

To show the effectiveness of the dynamic channel selection scheme, we set up a small network as shown in Figure 6(a), and monitor the variations of the number of packets overheard in a specific node when its battery voltage (and hence, its capacity B) is changed manually. Initially, the battery capacities of all nodes are made to be 100%. After 30 minutes, the battery voltage of node D is reduced manually using a voltage regulator to represent a battery

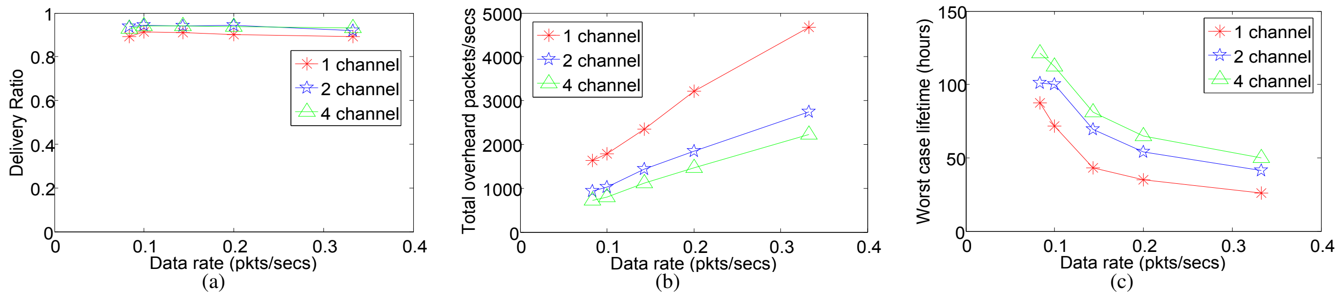

Figure 7. Comparison of (a) packet delivery ratio (b) network-wide packets overheard (c) worst case network lifetime with different data rates

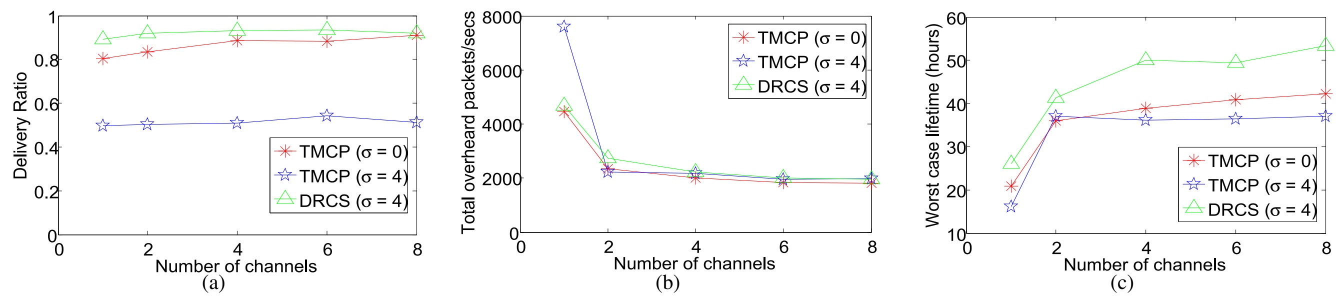

Figure 8. Comparison of (a) packet delivery ratio, (b) network-wide packets overheard (c) worst case network lifetime with different number of channels

capacity of 50%, keeping all others unchanged. In this experiment, we use only 2 channels and a data interval of 15 seconds. Figure 6(b) shows the variation of the number of packets overheard by D over time. Each bar on the x-axis shows the number of overheard packets by D over a duration 5 minutes. It can be observed that after 30 minutes the overhearing on node D starts reducing as all other nodes switch their transmit channels to avoid the receiver channel of D. This experiment demonstrates that our proposed scheme helps in reducing energy consumption at a node with bad health-metric, which can occur due to deteriorating battery health.

B. Simulation Results

We conduct simulations to evaluate the performance of our proposed scheme in a larger network and to also evaluate the lifetime improvement achieved by DRCS. We consider a network of 150 nodes that are uniformly placed in an area of 200×200 meters. The transmission power is assumed to be 0 dBm. The initial battery capacities of the nodes are assumed to be uniformly (randomly) distributed between 75% to 100%. The capacity of a fresh battery (100% capacity) is assumed to be 5000mAH. The beacon interval is set to 30 seconds and the maximum retransmission count is set to 30. Each simulation is run for 500 seconds and all the results are averaged over five independent simulations.

Comparison with different datarates: Fig 7 shows the variation of the packet delivery ratios, overhearing counts and the *worst case network lifetime* with different number of channels and transmission rates. Note that the performance of DRCS using a single channel is essentially the same as that of CTP. The worst case network lifetime is defined as the time when the first node of the network dies. It is observed that the packet delivery ratio is above 90% for all cases. This is consistent with the findings from the experimental testbed, indicating that at these data rates, the packet delivery ratio is not significantly affected by the channel switching scheme employed in DRCS. However, overhearing is reduced by nearly 40% with 2 channels and by over 50% with 4 channels. This significantly reduces the average current consumption in the nodes and improves the network lifetime.

Comparison with TMCP [9]: Fig 8 shows the comparison of DRCS with another well-known tree based multi-channel routing scheme TMCP for different number of channels. We assume a communication range of 40 meters and an interference range that is 1.5 times of the communication range. Here, we set the data interval to 3 seconds. Fig 8 shows that DRCS generates a higher packet delivery ratio in comparison to TMCP. This is due to several reasons. Firstly, TMCP uses a distance-based communication and interference model that does not effectively capture the link qualities, especially with a high channel variance σ^2. Secondly, DRCS uses channels more efficiently than TMCP. In TMCP nodes select the same channels as that of their parents. Hence, if the sink has n immediate neighbors and there are k channels where $k > n$, then at least $k - n$ channels will be unused, since there will be at most n sub-trees in the network. On the other hand, nodes on the same sub-tree in DRCS may use multiple channels, thereby improving channel utilization. Also in case of TMCP, the parent and channel assignments are static. These do not change even with variations of congestion and link quality. These result in poor route quality that leads to higher packet loss, retransmissions, and overhearing. Moreover, the channel quality may vary over time, which requires a dynamic protocol. It should be noted that the performance of DRCS and TMCP are similar in terms of the total reduction of overhearing with multiple channels. However, DRCS provides a much higher network lifetime that is achieved by dynamically balancing the lifetimes of individual nodes.

VI. Conclusions

In this paper, we propose a scheme for building a multi-channel tree in data gathering wireless sensor networks for maximizing the network lifetime. The proposed scheme DRCS involves distributed channel selection to enable nodes to reduce overhearing, and dynamic parent selection for minimizing the load of nodes that have the worst expected lifetime. Through simulations and experiments, we demonstrate that DRCS significantly improves the network lifetime without sacrificing the packet delivery ratio. The proposed scheme has no additional overhead other than periodic beacon updates, which makes it suitable for implementations in real-life applications to prolong the network lifetime.

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